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ACOUSTIC EFFICIENCY TRENDS FOR HIGH THRUST BOOSTERS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The acoustic efficiency indicative of the generated acoustic power of a system, was computed from measured farfield acoustic data to establish a general trend in production of acoustic power from the turbulent exhaust flow of a rocket as the mechanical power or thrust increases. The significance and limitations of presently adopted acoustic efficiencies are discussed, with a presentation of these computed efficiency values versus mechanical power. A more adequate method to define the true acoustic efficiency is also described briefly for static sound sources.

SECTION I. INTRODUCTION

For a turbulent flow system such as the exhaust flow of a rocket engine, the term denoting the ratio of acoustic power to mechanical power of the system has been defined as the acoustic efficiency. For a given system, the higher the value of the acoustic efficiency, the more noise or sound the system produces. For very high thrust rocket engines, or clusters of engines, the mechanical power produced grows quite large and the acoustic power increases also. The overall sound pressure levels produced by the turbulent flow of the exhaust can be described quantitatively by the acoustic efficiency η . This value of η can thus be used in determining the average sound power emitted from a given rocket of known mechanical power. The importance of this term is accentuated when the enormous mechanical power produced by the Nova class vehicle is considered. To estimate adequately the acoustic power produced by future large space vehicles, something must be known of the trends of acoustic efficiency values with increases of vehicle thrust or mechanical power.

The acoustic efficiency could be presented as a function of the exhaust exit mach number, exit diameter or a combination of many parameters. However the author chooses here, for simplicity and for convenient use of common terms, that mechanical power be used as a basis of comparison for this presentation since this is a transmittal of information rather than a highly theoretical report.

SECTION II. DISCUSSION

The acoustic efficiency, η , calculated from rocket engine tests, is obtained from the measured overall sound pressure levels, (SPL), in db* and from known engine parameters for a given test. To aid in clarifying how the value of η is obtained from acoustic data, the following equations are given which lead to the expression of η as a function of SPL. A definition of the acoustic efficiency is:

$$\eta = \frac{W_a}{W_m} \quad (1)$$

W_a = acoustic power (watts)
 W_m = mechanical power (watts)
 $W_m = .678$ (Thrust) x (Effective Exhaust Velocity)

The acoustic power level PWL in db is given by:

$$PWL = 10 \log \left[\frac{W_a}{W_o} \right] \text{ db} \quad (2)$$

W_o = reference power 10^{-13} watts

By combining equations 1 and 2 the PWL is given by:

$$PWL = 10 \log \left[\eta \frac{W_m}{W_o} \right] \text{ db} \quad (3)$$

The power level, PWL is also defined as:

$$PWL = \overline{SPL} + 10 \log A \quad \text{db.}$$

Solving for \overline{SPL} , the space average overall sound pressure level,

* db reference to 0.0002 dynes/cm²

$$\overline{\text{SPL}} = \text{PWL} - 10 \log A \quad (4)$$

A = Area through which
acoustic power is
radiated (ft²)

Combining equations 3 and 4

$$\overline{\text{SPL}} = 10 \log_{10} \left[\eta \cdot \frac{W_m}{W_o} \right] - 10 \log_{10} A \quad (5)$$

The $\overline{\text{SPL}}$ from test to test or from various test geometries can vary for the same engine or engines depending on many factors. The test area geometry, the deflector configuration, or the nozzle expansion ratio, for example, can affect the measured sound pressure levels about the source and possibly alter the space average SPL or $\overline{\text{SPL}}$.

Should two tests of the same engine with sound measurements at an equal radius and angular orientation from each engine produce different $\overline{\text{SPL}}$'s, the corresponding value of η would also vary. For example consider a Test #1 and a Test #2, both exhibiting equal mechanical power, employing sound measurements for each at equal radii and angles from a reference.

The $\overline{\text{SPL}}$'s can be expressed from equation 5 as

$$\overline{\text{SPL}}_1 = 10 \log_{10} \left[\eta_1 \frac{W_{m_1}}{W_o} \right] - \log_{10} A_1 \quad (6)$$

$$\overline{\text{SPL}}_2 = 10 \log_{10} \left[\eta_2 \frac{W_{m_2}}{W_o} \right] - \log_{10} A_2 \quad (7)$$

Since R_1 and R_2 are equal, then the areas A_1 and A_2 are eliminated when combining equations 6 and 7 as

$$\overline{\text{SPL}}_1 - \overline{\text{SPL}}_2 = 10 \log_{10} \left[\eta_1 \frac{W_{m_1}}{W_o} \right] - 10 \log_{10} \left[\eta_2 \frac{W_{m_2}}{W_o} \right] \quad (8)$$

Since the mechanical powers developed by each engine are equal, then equation 8 becomes

$$\overline{\text{SPL}}_1 - \overline{\text{SPL}}_2 = 10 \log_{10} \left[\frac{\eta_1}{\eta_2} \right] \text{ db} \quad (9)$$

Should there be 3 db difference in the $\overline{\text{SPL}}$'s under these conditions, it is seen that the value of the acoustic efficiency is affected by a factor of two; thus illustrating the criticalness of the η values with variations in the $\overline{\text{SPL}}$'s. To accurately evaluate the acoustic efficiency, remembering the criticalness of η with $\overline{\text{SPL}}$ variations, the corresponding $\overline{\text{SPL}}$ should have the desired statistical acceptability. By using less than an adequate number of sound measurements to determine the $\overline{\text{SPL}}$ from a sound source, insufficient accuracy may be obtained thus radically affecting the η value. A more detailed discussion of the adequate measuring program is given in Section III.

To further relate the acoustic efficiency and the sound pressure level, solving equation 5 for η gives

$$\eta = \left(\frac{\overline{\text{SPL}}}{10^{10}} \right) \left(A \frac{W_o}{W_m} \right) \quad (10)$$

This equation can be used readily for η calculations with given variables,

$$\text{Where } A = 2 \pi R (R + H) \text{ (ft}^2\text{)}$$

$$H = \text{source altitude (ft)}$$

$$R = \text{source-receiver distance (ft)}$$

$$W_m = .678 \text{ TV (watts)}$$

$$T = \text{Thrust (lb) (assumed to be known)}$$

$$V = \text{exhaust gas velocity (ft/sec) (assumed to be known)}$$

Effects due to reflecting planes such as complex test area geometry can influence the sound field about the sound source and thus possibly influence the calculation of a valid value of η . In general it is imperative to point out that the acoustic efficiency could be highly dependent on the specific test geometry or the monitoring positions where the sound pressure levels are measured. It should be remembered that especially in small model studies where high frequencies are easily reflected, that geometry may be more critical than in prototype studies, thus more readily affecting the sound field giving erroneous η values for representation of free field test conditions.

SECTION III. VALID DETERMINATION OF THE ACOUSTIC EFFICIENCY

To accurately determine the value of η for a point sound source, i. e. from a farfield location, certain conditions should be met in obtaining the data:

1. The sound source should be located at the center of a coordinate system for convenience.
2. Monitoring points at which microphones are to be positioned should be in a farfield area from which the sound source can be considered a point source.

The radius of measuring positions should not be so great as to introduce appreciable errors from molecular absorption. (This molecular absorption can be determined for a given frequency range by referring to acoustic literature, to data from the appropriate frequency range.) A number of measurements of the overall sound pressure level, on a spherical or hemispherical surface - - or even the surface of an octant--if symmetry permits, must be made to evaluate the sound pressure levels all around the source or over an acoustically symmetrical section to evaluate a valid value of η for a directional source. If a hemispherical surface is considered for measurement, then the area A (Hemisphere), $A_{(H)}$, should be divided into 20 equal components of area $\frac{A_H}{20}$, for example, with the microphone placed at the center of each component area $\frac{A_H}{20}$, at the radius R of the hemisphere. The total acoustic power radiated is thus determined by summing the intensities over each component area $\frac{A_H}{20}$. The suggested number of microphones or component areas and other detailed information are in Reference 1. In obtaining measurements at positions indicated above, the space average overall sound pressure level, SPL, can be determined more reliably than from several measurements in one plane only.

When rocket engines are tested they are usually located on a hold-down arrangement, with acoustic measurements made on or near the

ground plane. Needless to say, with only ground plane measurements, the limited data recorded may not be representative of the true acoustic power of the source. But, the data recorded from ground measurements can provide representative values of η for the ground plane area considering that specific test configuration.

Acoustic measurements in other planes, as indicated in this section and in Reference 1, are needed to determine more accurately the values of η for a given test configuration. When it is necessary to describe the acoustic field three-dimensionally, it is worthwhile to direct further effort toward this type of study. An example of this need may be found in problems associated with vehicle launch in which the acoustic efficiency and the source directional characteristics are of benefit in farfield studies.

SECTION IV. DISCUSSION OF PRESENT VALUES OF ACOUSTIC EFFICIENCY

The values of the acoustic efficiency η for almost all the engines considered in this report were obtained from acoustic measurements in the ground plane with the engine or engines in a hold-down position from one to (approximately) ten nozzle diameters above the ground plane. In some engine tests the measurements hardly provide enough data, due to the inadequate number of measurements that were made, to calculate a valid value of η even for the ground plane. The values of η given in this paper (curve A of Fig. 1) were obtained from tests of rocket engines producing up to 1.5 million pounds of thrust in which a deflector either of the bi-directional wedge type or the uni-directional flow bucket type was used. One exception to this is the 500 K solid propellant engine that was fired horizontally (Ref. 2). Configuration of the deflector affects the SPL's at certain locations with respect to the exhaust flow, and therefore alters the calculated value of η which is dependent on the SPL's that are measured in the ground plane at various farfield positions about the source.

The data presented here, in acoustic efficiency form (curve A of Fig. 1), is the average of the data and is considered representative of the exhibited acoustic environments for ground plane areas as mentioned above (Ref. 3-8). These values of the acoustic efficiency (determined from ground plane measurements) do not necessarily represent the true acoustic efficiency exhibited by the rocket exhaust stream; however, they should show a reliable trend, from the similarity of the areas from which the data were acquired.

Curve B of Figure 1 denotes a much greater rate of increase in η with higher mechanical power outputs than does curve A. It should be noted here that curve B evolved from acoustic data from rockets producing less than 150,000 pounds thrust and extropolation of η from curve B to much higher mechanical power outputs can be seen to result in much higher η values than was indicated from measured data as reported in References 2 through 8.

For example it can be shown from Reference 10 (from the equation form of curve B of Figure 1 as shown in this report) that a two per cent acoustic efficiency is indicated for a mechanical power of 1×10^{10} watts whereas only approximately 0.5 per cent has actually been measured from tests.

ACOUSTIC POWER WATTS
MECHANICAL POWER WATTS $\times 100 =$ ACOUSTIC EFFICIENCY η in %

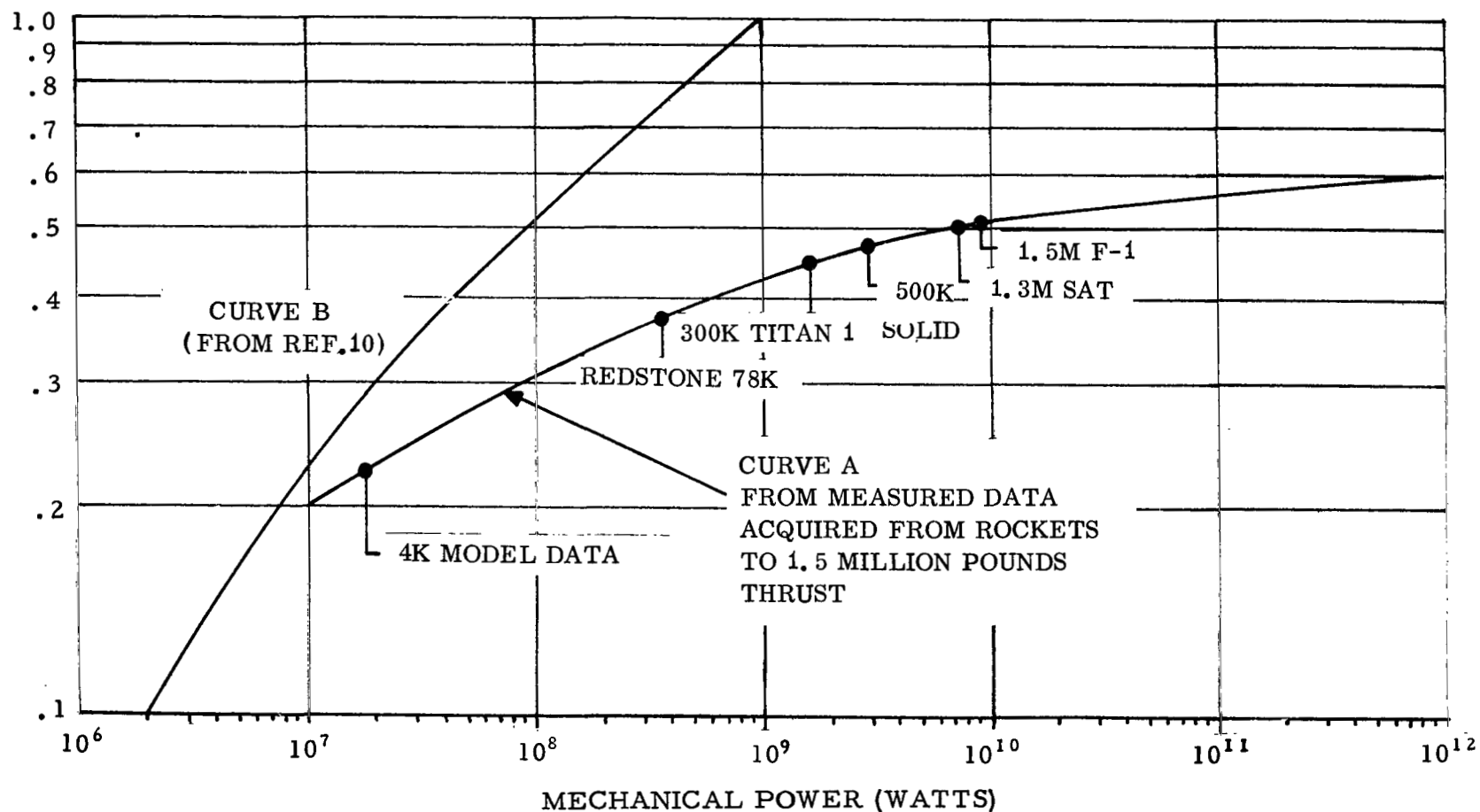


FIGURE 1. ACOUSTIC EFFICIENCY TRENDS

SECTION V. CONCLUSIONS

Values of the acoustic efficiency were calculated from measured farfield sound pressure level data. These values represent the acoustic efficiency exhibited to the ground plane when the vehicle or engine is in a vertical position, (excluding the case of Reference 2) exhausting to a uni-directional bucket or bi-directional wedge deflector (Ref. 3-8).

A trend in the rate of increase of the acoustic efficiency is indicated from the plot (curve A of Figure 1) of η versus jet mechanical power. Data from rockets producing from 1×10^6 to 1×10^{10} watts of mechanical power show an ever-increasing value of η -- but at a decreasing rate of growth with higher mechanical power outputs. This decreasing rate of change in the acoustic efficiency is significant: for increasing mechanical power outputs, the rate of η increase tends to approach zero, or η tends to approach a constant value. This plateau-trend in the acoustic efficiency tends to be initiated at approximately 5×10^9 watts of mechanical power. It is anticipated from this trend that the η value will not greatly exceed 0.5 per cent for further increases in mechanical power outputs (considering conventional rocket engine designs and herein listed conditions). In basis agreement with this trend, a theoretical analysis by M. J. Lighthill (Ref. 9) has also indicated an upper limit for the value of η at approximately 0.6 per cent.

The conclusions are that the acoustic efficiency increases with mechanical power, but the rate of increase appears to diminish with higher mechanical power values and finally asymptotically approaches a constant value slightly higher than 0.5 per cent (curve A of Fig. 1). Since curve A of Figure 1 is based on data from engines of mechanical power outputs which are an order of magnitude higher than those represented by curve B, it is felt that curve A is more adequate for extrapolation of acoustic efficiency values for future conventional rockets of large mechanical power outputs.



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